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Simulations of carbon fiber composite delamination tests

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Abstract

Simulations of mode I interlaminar fracture toughness tests of a carbon-reinforced composite material (BMS 8-212) were conducted with LSDYNA. The fracture toughness tests were performed by U.C. Berkeley. The simulations were performed to investigate the validity and practicality of employing decohesive elements to represent interlaminar bond failures that are prevalent in carbon-fiber composite structure penetration events. The simulations employed a decohesive element formulation that was verified on a simple two element model before being employed to perform the full model simulations. Care was required during the simulations to ensure that the explicit time integration of LSDYNA duplicate the near steady-state testing conditions. In general, this study validated the use of employing decohesive elements to represent the interlaminar bond failures seen in carbon-fiber composite structures, but the practicality of employing the elements to represent the bond failures seen in carbon-fiber composite structures during penetration events was not established.

Introduction

Initiation and propagation of interlaminar failure (delamination) in fiber composites is of paramount importance in predicting the failure of composite structures. A program to simulate the performance of aircraft composite ballistic shields has been initiated and supported by the Federal Aviation Administration (FAA). Predicting the delamination between lamina of a carbon-reinforced composite during penetration by ballistic fragments is an important part of that FAA program. Fracture toughness tests of BMS 8-212 were performed by U. C. Berkeley [1] as an initial step toward achieving that goal. These tests were designed to produce fracture toughness values for BMS 8-212 (grade 190, type 3, class 1 as classified by Boeing and made by Hexel), a material that is representative of generic composite panels that could be employed in aircraft shielding systems.

This report describes the simulations of the U.C. Berkeley fracture toughness tests through the use of delamination (decohesive) elements to connect the lamina in the BMS 8-212 lay-up. The simulations were performed to investigate the validity and practicality of employing decohesive elements to represent the interlaminar bond failures seen in carbon-fiber composite structures during penetration events.

Delamination elements, ideally of zero thickness, have a prescribed traction versus crack opening displacement (relative displacement between the two connected lamina) rather than the stress versus strain relationships found in more conventional element formulations. Delamination (element failure) between plys in the decohesive element formulation is governed by element energy release/crack opening length. The failure is (or should be) mesh independent. The energy released during the tensile failure of a conventional element can be dependent on the element thickness unless some energy regularization scheme is utilized, e.g., a characteristic length embedment into the element. Typically, in a decohesive element, a maximum traction (normal stress) is associated with an initial crack opening as well as a maximum crack length that is associated with zero bond strength. A typical traction versus crack opening curve is shown in Figure 2. The fracture toughness of the bond between the lamina of the composite plys (a material input) is equal to the integral of the element traction versus crack opening.

In this study, the delamination element mesh independence was first verified on a simple two element model before being employed to simulate the U.C. Berkeley fracture toughness tests. Varying mesh densities and loading rates were explored in this study. Additional care was required in the study to ensure that the explicit time integration of LSDYNA duplicate the near steady-state testing conditions.

<u>Verification of the LSYNA delamination element</u>

The LSDYNA delamination material model (*MAT_COHESIVE_TH) was developed by Tvergaard and Hutchinson. An informative paper describing the formulation and implementation of decohesive elements can also be found in [2]. The LSDYNA delamination element mesh sensitivity to energy release was verified with a simple two element model that is shown in Figure 1. For the verification, a constant velocity was applied to the upper block, holding the lower block fixed. The two blocks were connected by a zero thickness delamination element. The resulting traction versus upper block displacement results for varying mesh sizes (by an order of magnitude) and loading rates are shown in Figure 2. For these results, the integral of the traction versus crack opening (upper block vertical displacement) was equal to the input fracture toughness of the bond between the two blocks. As can be seen, the energy release/crack area was invariant for the situations considered.

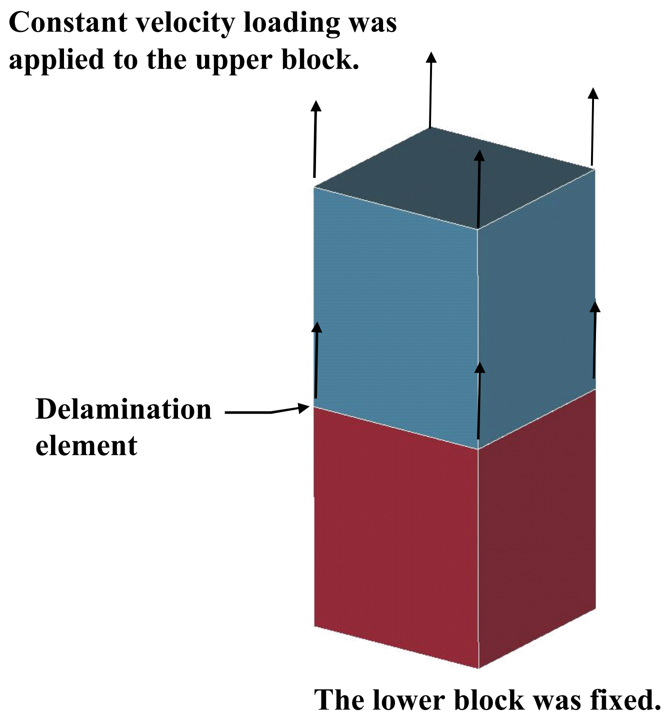


Figure 1. Simple two block mesh for delamination element verification.

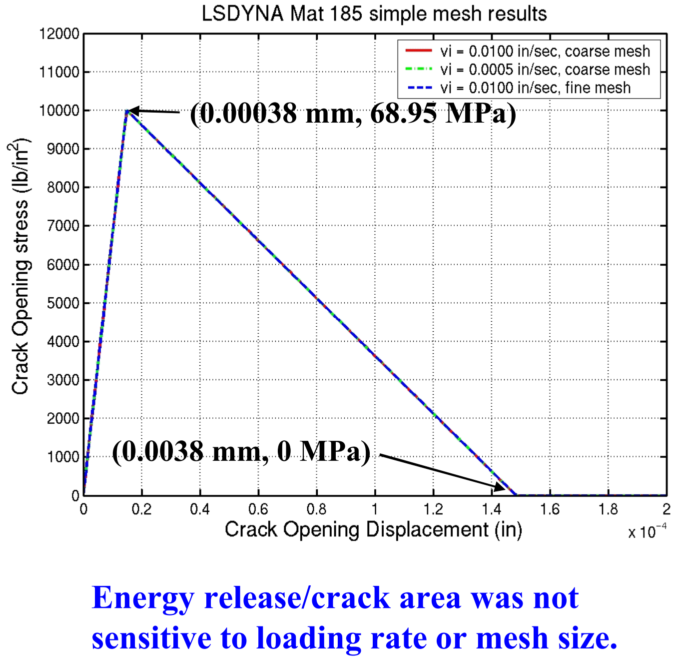


Figure 2. Delamination element verification results.

Simulation of the U.C. Berkeley interlaminar toughness tests

The BMS 8-212 delamination test simulation specimen, shown in Figure 3, was a unidirectional 24 ply beam that was 125 mm long, 24 mm wide and 4.75 mm thick, with a 38.1 mm initial crack at mid-height. The 4.75 mm thickness was somewhat lower than the tested thicknesses which varied from 4.86 mm to 5.91 mm (the actual thicknesses were not available at the time that this study was performed). These reduced thicknesses (of double cantilever beams originating at the origin of the cracks) resulted in reduced simulated beam stiffnesses of as much as 0.519 of the actual beam stiffnesses. In the model, symmetry was assumed to exist along a vertical plane at the half width of the beam. Symmetry was also assumed between the upper and lower sections of the cantilever test specimen. In the simulations, delamination elements were used to connect beam solid elements to the assumed horizontal symmetry plane. The coarse mesh of this study contained 36,040 nodes and 28,528 solid elements. In Figure 3 the model has been reflected about both symmetry planes for visualizations purposes.

The cantilevered beam section in this analysis was defined with either three or four element though the thickness. Those mesh resolutions resulted in solid element depths 0.792 mm and 0.594 mm. Element lengths in the horizontal plane were kept between 0.75 and 1.0 of the through-the-thickness element lengths. That element side ratio constraint and the overall problem size limited the number of elements that could be used through the thickness of the beams in the delamination specimen. This led to beam sections that were slightly under defined as to the elastic bending stiffness at the outer surface. The outer integration point was located off the neutral axis by a distance equal to one third of the total beam thickness in the meshes that employed three (through the thickness) single integration point solid elements. In the test specimens, the outer fiber was located off the neutral axis by a distance equal to one half of the total beam thickness. Increasing the number of through the thickness elements from 3 to 4 resulted in a minor bending stiffness increase as will be discussed later.

To test the effect of loading rates, constant velocities of either 1270 mm/sec or 559 mm/sec were applied directly to the beam ends. These rates were chosen because they were both much longer than the natural period of an un-cracked beam of the same dimensions. This was done to avoid the inertia activation problems inherent in trying to use an explicit code to model quasi-static loading events. These rates were probably still too fast as they resulted in a crack velocities that were noisy and somewhat chaotic in nature.

A triangular shaped traction/crack opening relationship was chosen for these calculations. The integral of the relationship, as specified by the U.C. Berkeley results, was 130 J/m^2. The maximum allowable traction was chosen to be 79.3 MPa, and the rise distance and maximum allowable failure lengths were chosen to be 0.00033mm and 0.0033mm respectively. These values were chosen after conversations with knowledgeable personnel at LLNL. The complete LSDYNA input for the delamination elements are given in Appendix A.

In the determination of the BMS 8-212 unidirectional laminate properties it was assumed that the carbon fibers were essentially rate insensitive and brittle in their stress-strain responses. Furthermore it was assumed that the beam response was elastic with the exception of the cohesive zone between the upper and lower beam sections. The lamina (ply) properties for BMS 8-212 given in Appendix B are for use in a constitutive model that assumed an orthotropic elastic *averaged* behavior for each element. For a multi-angle composite, this would imply pre-possessing of the plys contained in each element to produce the required averaged behavior input for the constitutive model. Alternatively, if the thickness of each element represented a single ply of a laminate material then lamina properties could be used as the constitutive model input. These restrictions were not assumed to apply in the case of a unidirectional laminate, i.e., the unidirectional lamina properties were assumed to be applicable to elements that contained many ply layers. The elastic properties for the lamina material are from Boeing and from communications with Steve DeTeresa at LLNL.

Results

Comparisons are made with U.C. Berkeley test data from specimens 1 and 4 in Figure 4. The results are noisy, but did not significantly change when the number of elements through the thickness was increased from three to four. The results also did not show much change when the crack opening loading rate was decreased from 1270 mm/sec to 559 mm/sec. The results were filtered with a low pass cutoff frequency of 1,000 Hz to reduce noise. Sample calculated crack opening displacements versus the crack extensions are compared in Figure 5. The simulation does a fair job at reproducing the dynamic crack growth rate of the test.

The initial slope of the calculated crack opening force versus crack displacement relationship is equal to the stiffness of the double cantilever beams originating at the origin of the crack. In the initial phase of this study it was found that this slope was too soft when the available BMS 8-212 unidirectional lamina data was used. For these calculations the Young's modulus for the unidirectional laminate material fiber direction was increased by a factor of 3.75 over the suggested BMS 8-212 lamina values in order to match the test data (13,790 MPa was increased to 51,713 MPa). In retrospect, the 3.75 stiffness increase in the fiber direction lamina properties may not have been entirely necessary as the difference between the assumed and actual beam geometries could have accounted for a stiffness difference of as much 1.93. The effect of increasing the apparent beam stiffness by increasing the number of through the thickness elements from 3 to 4 can be seen in Figure 4 by a slight increase in the crack opening force versus crack displacement slope for the more finely resolved beam.

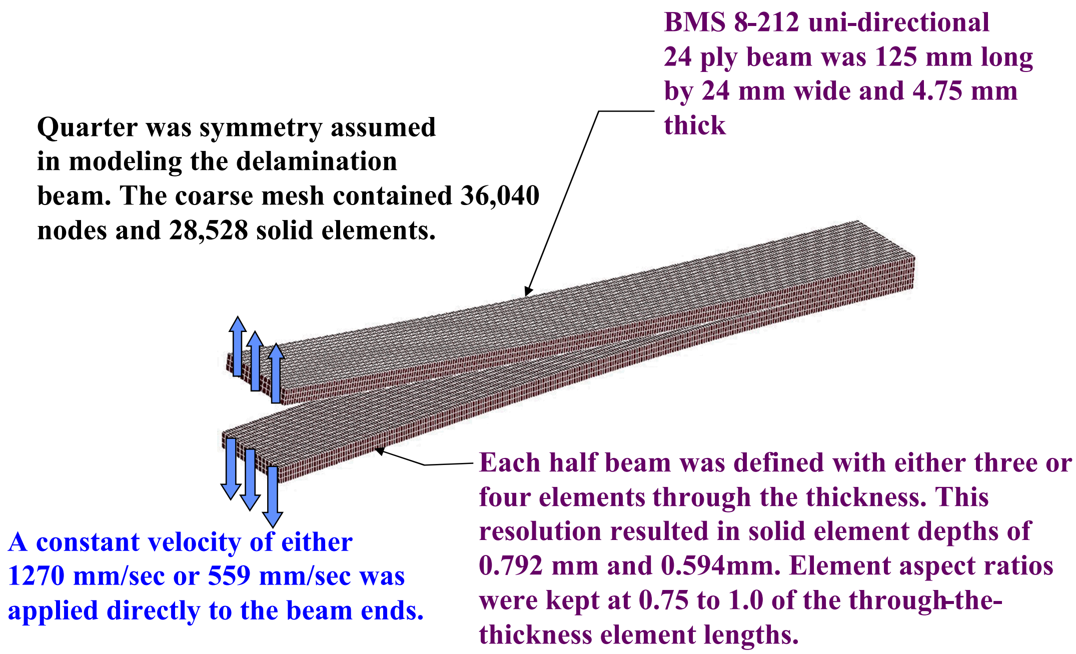


Figure 3. Delamination mesh.

Observations and Conclusions

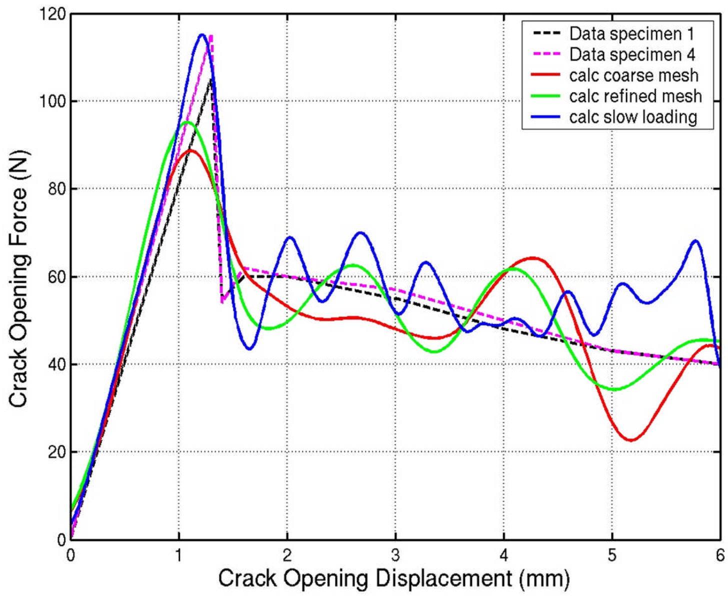
1) In general, this study validated the use of decohesive elements to represent interlaminar bond failures seen in carbon-fiber composite structures. The delamination test simulation results were fairly accurate, but noisy and expensive, taking about 10 hours on a single processor SGI workstation.

The practicality of employing decohesive elements to represent the interlaminar bond failures seen in carbon-fiber composite penetration events could be established with penetration simulations that employ decohesive elements between carbon fiber lamina or laminate elements. It would also be useful to perform comparison calculations with shell/decohesive elements units rather than the solid element/decohesive element units of this study.

2) The traction/crack opening results were somewhat insensitive to the maximum allowable matrix material tensile strength.
3) The decohesive element's energy release insensitivity to mesh density worked as advertised but overall noise in the results varied with loading rates and mesh density. This noise could probably be reduced by finer meshes that employ many (3 to 5) elements in the zone around the moving crack tip. That degree of resolution was not possible in these simulations due to memory

problems in the version of LSDYNA (ls971_6863_d_alpha_51a-p) that was used in this study (that problem has since been fixed).

4) The need for the increased longitudinal unidirectional BSM 8-212 lamina properties that were required in this study (to match the initial cantilevered beam sections stiffnesses) needs to be understood if these values are to be used in future penetration simulations where bending is occurring. In this study, zero degree BSM 8-212 lamina properties were used to represent averaged laminate properties in the finite element mesh. If this assumption was correct then the BSM 8-212 that was tested was stiffer than expected in the fiber direction or, the original homogenizing scheme that was employed to determine the BSM 8-212 lamina properties was not consistent with bending modes of deformation.
5) The sensitivity of the results of this study to the use of actual specimen thicknesses and nominal unidirectional BSM 8-212 lamina stiffnesses should also be determined. The initial traction/crack opening slope will probably still be too low, but the overall correlation between the measured and calculated crack opening forces versus crack displacements might still be sufficient to justify the use of this mesh resolution and the nominal lamina properties. It would also be useful to perform this calculation with shell/decohesive elements units to access the limitations of the single integration point solid elements in bending dominated environments.



Data specimen 1
Data specimen 4
calc coarse mesh
calc refined mesh
calc slow loading
Crack Opening Force (N)
Crack Opening Displacement (mm)
0
20
40
60
80
100
120
0
1
2
3
4
5
6

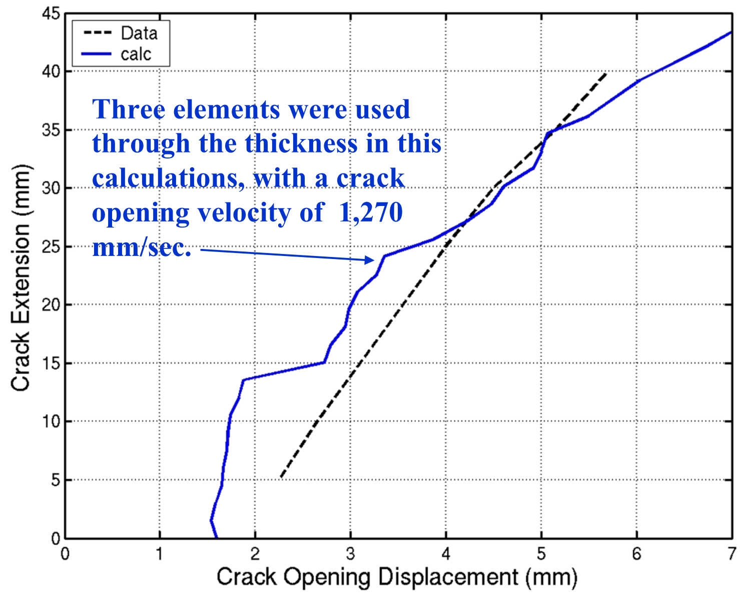


Figure 5. Crack extension versus crack opening displacement for the coarse mesh and the faster crack opening velocity.

References

1) Johnson G. C., Donovan, K., Kashevaroff, D., "Determination of the Interlaminar Toughness and Ballistic Characteristics of Unidirectional BMS 8-212 Composites", Department of Mechanical Engineering, University of California, to be published.
2) Pinho, S.T., Iannucci, L., Robinson, P., "Formulation and implementation of decohesion elements in an explicit finite element code", Composites Part A: applied science and manufacturing, Elsevier Ltd (2005
3)

Appendix A. BMS 8-212 Unidirectional laminate cohesive element input

Density	1,550 Kgm/m^3
Fracture toughness	130 J/ m^2
Maximum traction	79.293 MPa
Crack opening displacement to peak traction	0.00033 m
Complete failure crack displacement	0.0033 m

Appendix B. BMS 8-212 input for LSDYNA constitutive model *MAT_ORTHOTROPIC_ELASTIC_MODEL

For the uni-directional lamina, the A direction is the fiber direction, B the transverse direction and C is the normal direction.

Density	1,550 Kgm/m^3	
E_a	11,790 to 13,790 MPa	Young's modulus in the longitudinal direction (original value range from the literature)
E_a	51,710 MPa	Young's modulus in the longitudinal direction (value used in this study)
E_b	8,826 MPa	Young's modulus in the transverse direction
E_c	8,826 MPa	Young's modulus in the normal direction
ν_{ba}	0.02545	Poisson's ratio
ν_{ca}	0.02545	Poisson's ratio
ν_{cb}	0.30000	Poisson's ratio
G_{ab}	4,551 MPa	Shear modulus in the ab plane
G_{bc}	4,551 MPa	Shear modulus in the bc plane
G_{ca}	4,551 MPa	Shear modulus in the ca plane